# First Stage of Recovery in the Stratospheric Ozone Layer

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# The ozone trend model

$[O3]_t = \mu + \omega t$ + [Seasonal terms] + [QBO periodic terms] + $\gamma$ $[F10.7]_t + N_t$

$\mu$ is the mean level,

$\omega$ is a linear trend coefficient,

the seasonal terms represent the 12-, 6-, 4-, and/or 3-months cosine terms each with a time lag

The QBO periodic terms consist of cosines with time lags to represent QBO signal with periods between 3 and 30 months excluding 12-, 6-, 4-,and/or 3-months terms. The traditional approach of using Singapore winds with a fitted lag produces similar results, but with less precise trend estimates and more fluctuations in the residuals.

$[F10.7]_t$ is the F10.7-cm radio flux density which is used to provide a solar variation proxy.

$\gamma$ is a solar signal regression coefficient.

Nt is the autocorrelated error term, for which a first order autoregressive process is assumed ($N_t = a_1 N_{t-1} + \varepsilon_t$).

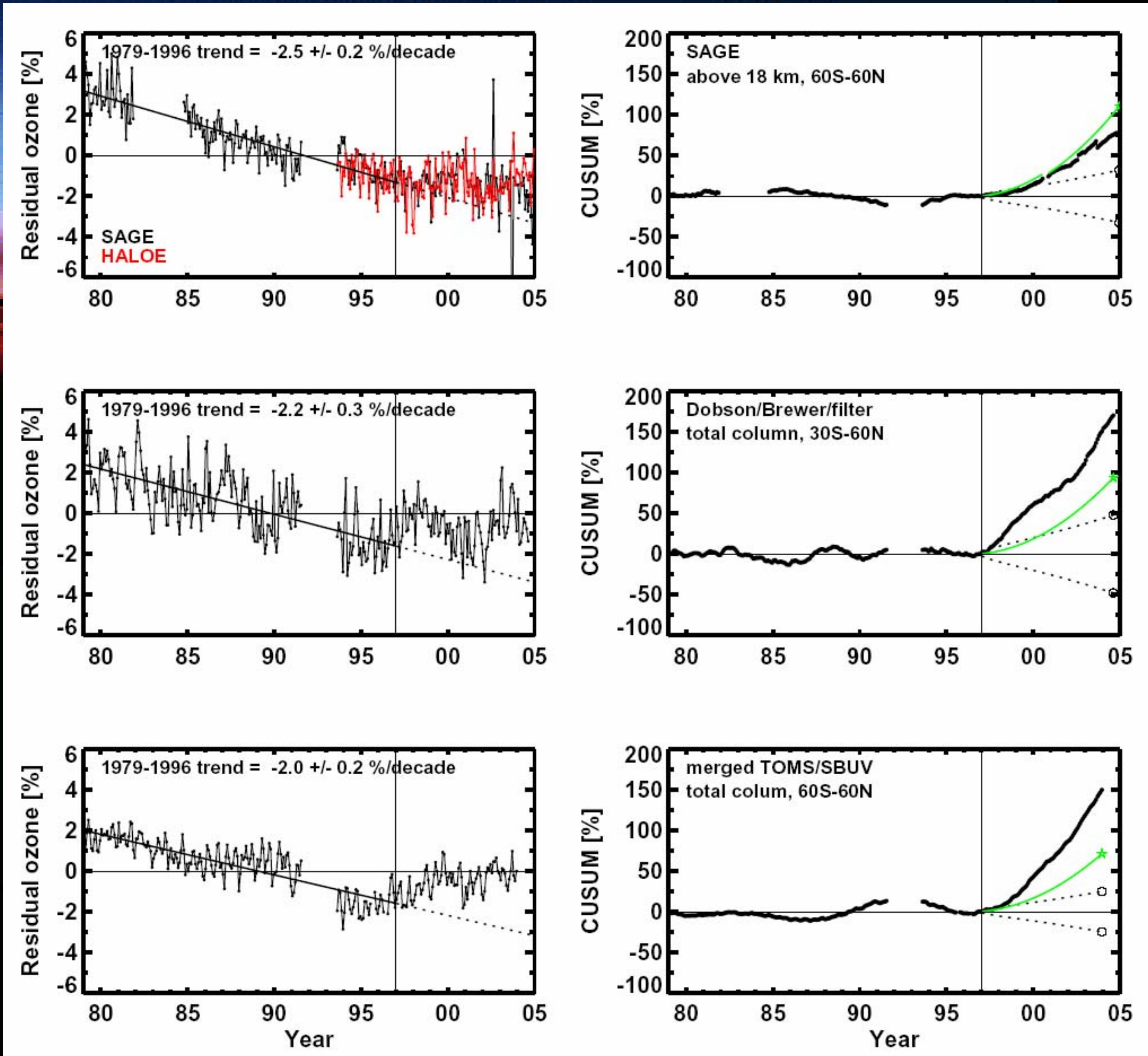
The $\varepsilon_t$ residuals, after removing the autoregressive component, $a_1 N_{t-1}$, are the residuals that are used to compute the cumulative sums of residuals described in Appendix B.

# Ozone trend+residual and Cumulative Sums

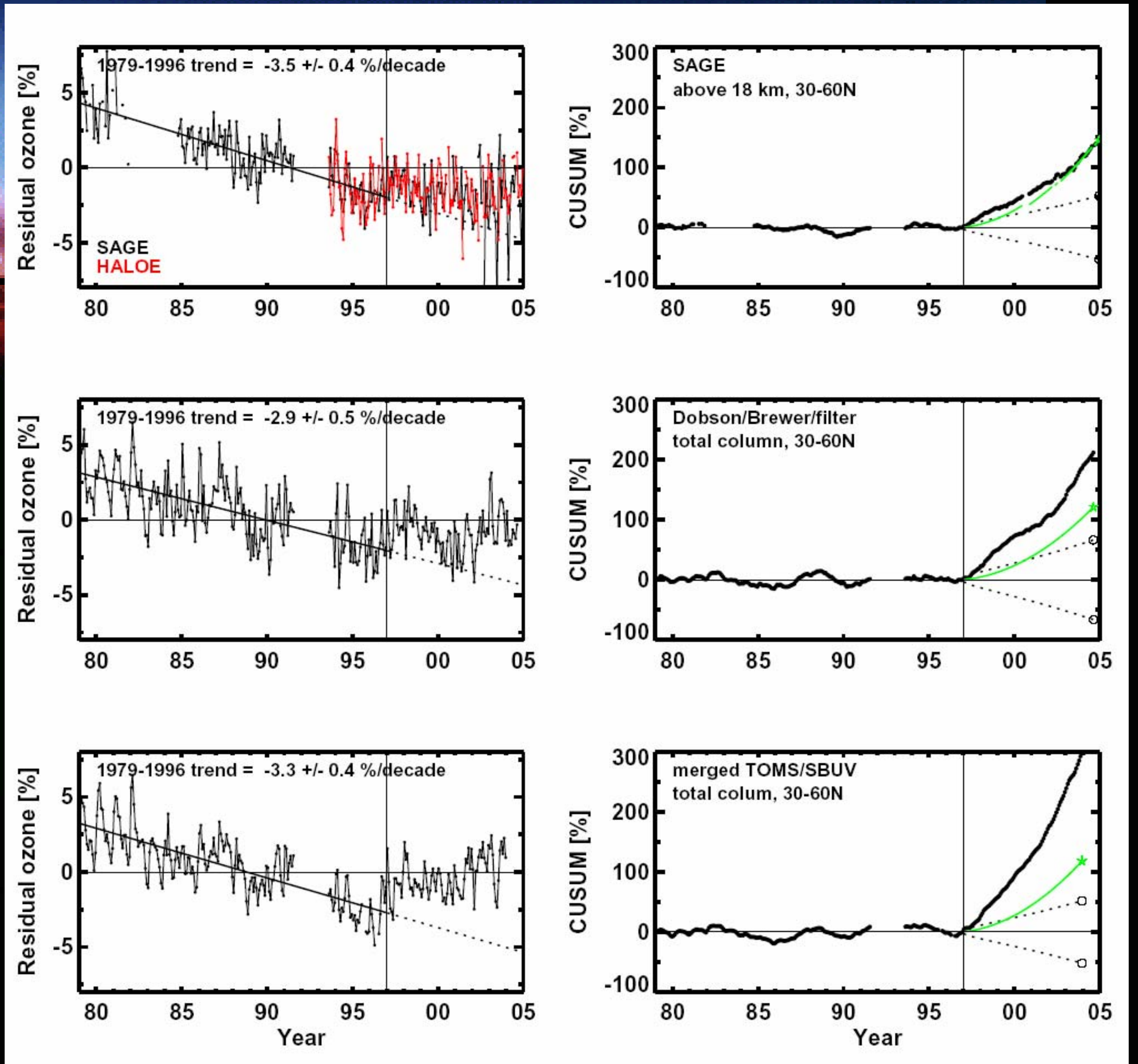
60S-60N SAGE and MOD
30S-60N ground sites

Green line represents constant ozone after 1997

2-sigma CUSUM [%] Envelope after 1997



# Ozone trend+residual and Cumulative Sums




**30N-60N**

**Three data sets:**

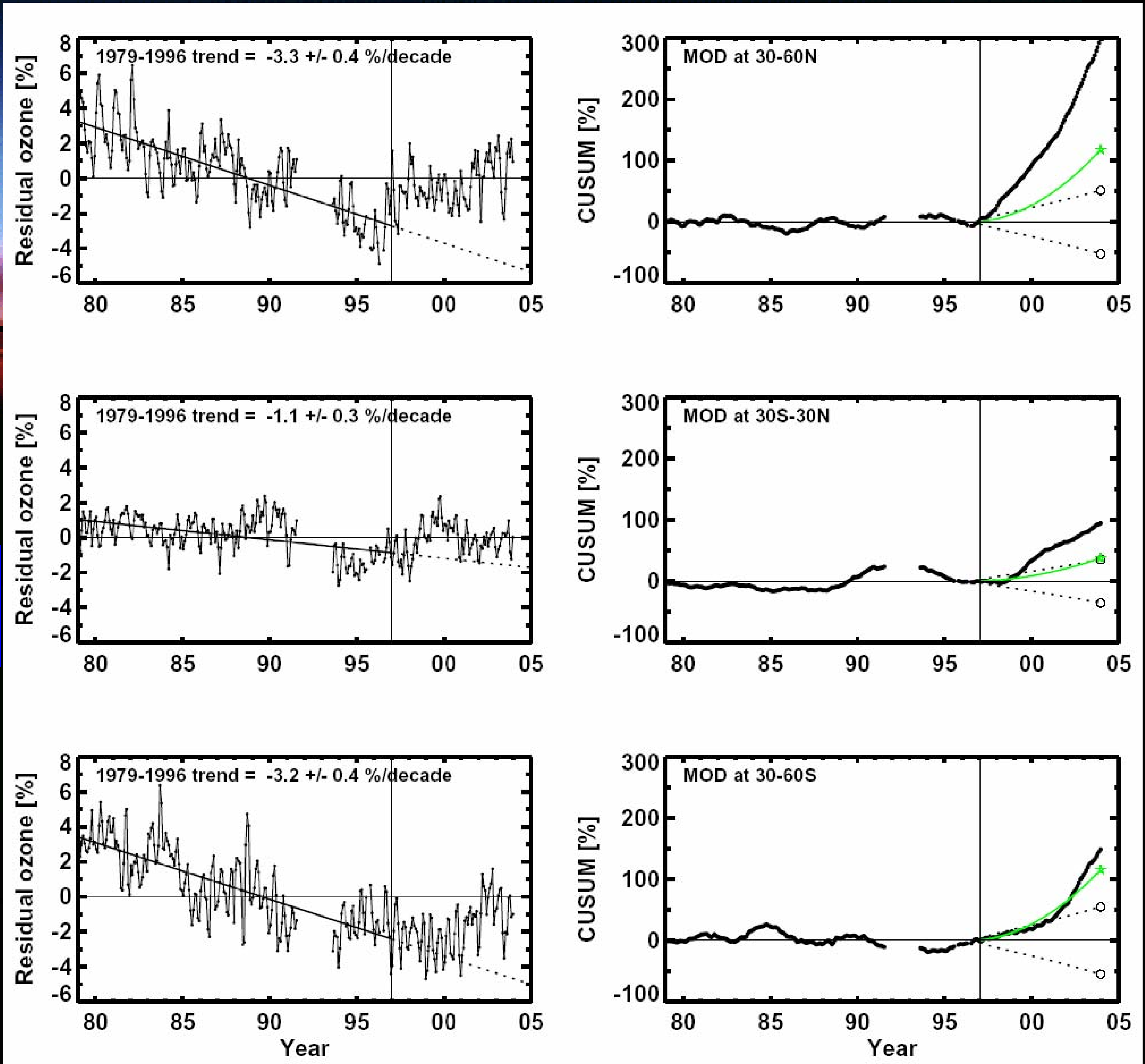
- **SAGE**
- **Dobson-Brewer**
- **Merged TOMS/SBUV**

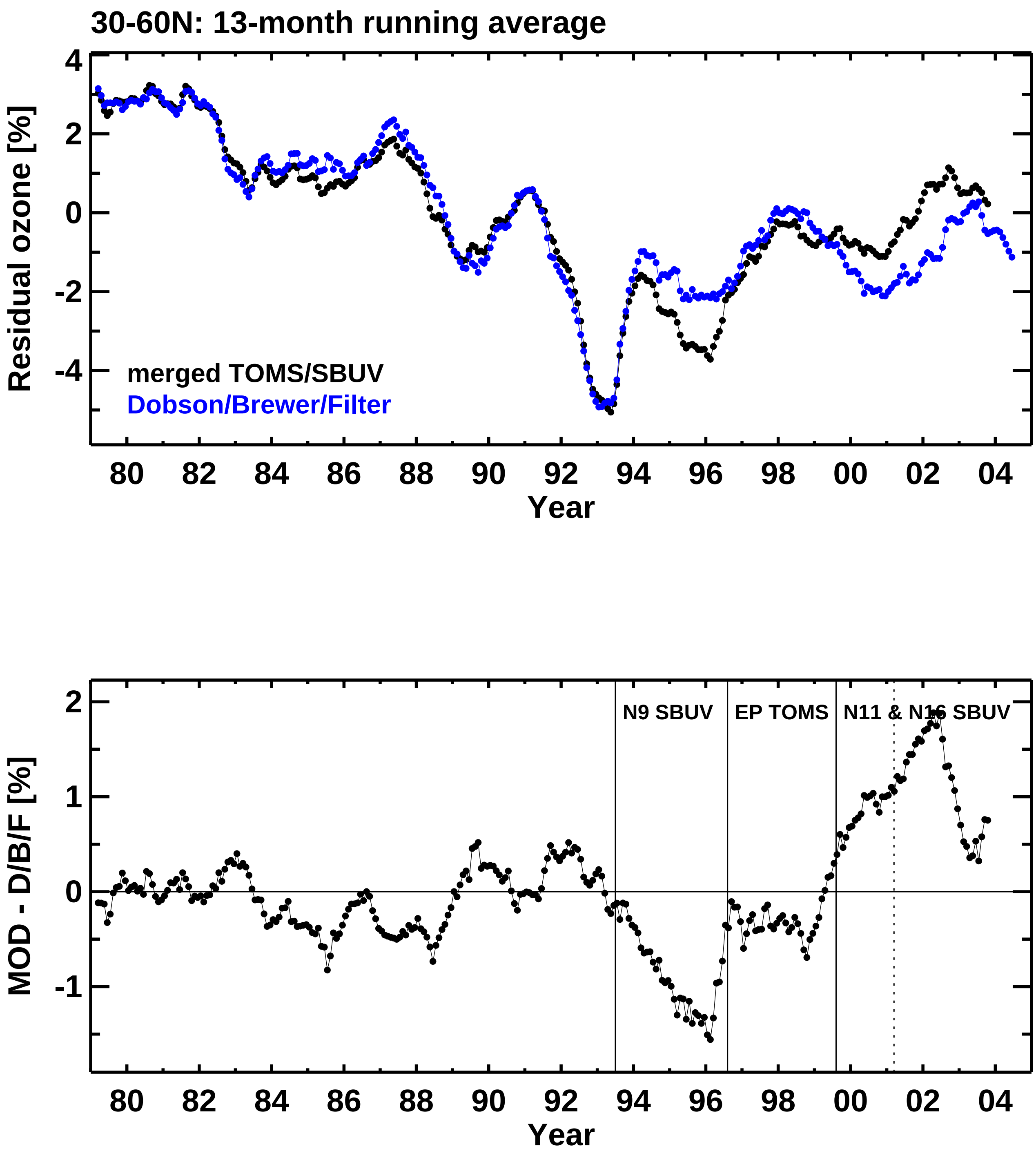
**Merged TOMS/SBUV shows different “recovery” signature than SAGE and Dobson-Brewer**

# MOD trend+residual and Cumulative Sums

**3 latitude bands**

**Merged TOMS/SBUV**





30-60N: 13-month running average
Residual ozone [%]
merged TOMS/SBUV
Dobson/Brewer/Filter
4
2
0
-2
-4
80
82
84
86
88
90
92
94
96
98
00
02
04
Year
MOD - D/B/F [%]
N9 SBUV
EP TOMS
N11 & N16 SBUV
2
1
0
-1
80
82
84
86
88
90
92
94
96
98
00
02
04
Year


Figure 2B

# Effective Equivalent Stratospheric Chlorine

## Photochemical model & EESC

Fractional halogen loss of $O_3$ constrained by:

- HALOE $CH_4$ : used to specify $Cl_y$, $Br_y$ & $NO_y$
- HALOE & SAGE $H_2O$
- SAGE Surface Area
- HALOE & SAGE $O_3$ and overhead $O_3$ column
- Pre-UARS trends in $H_2O$ & $CH_4$ based on SPARC & WMO

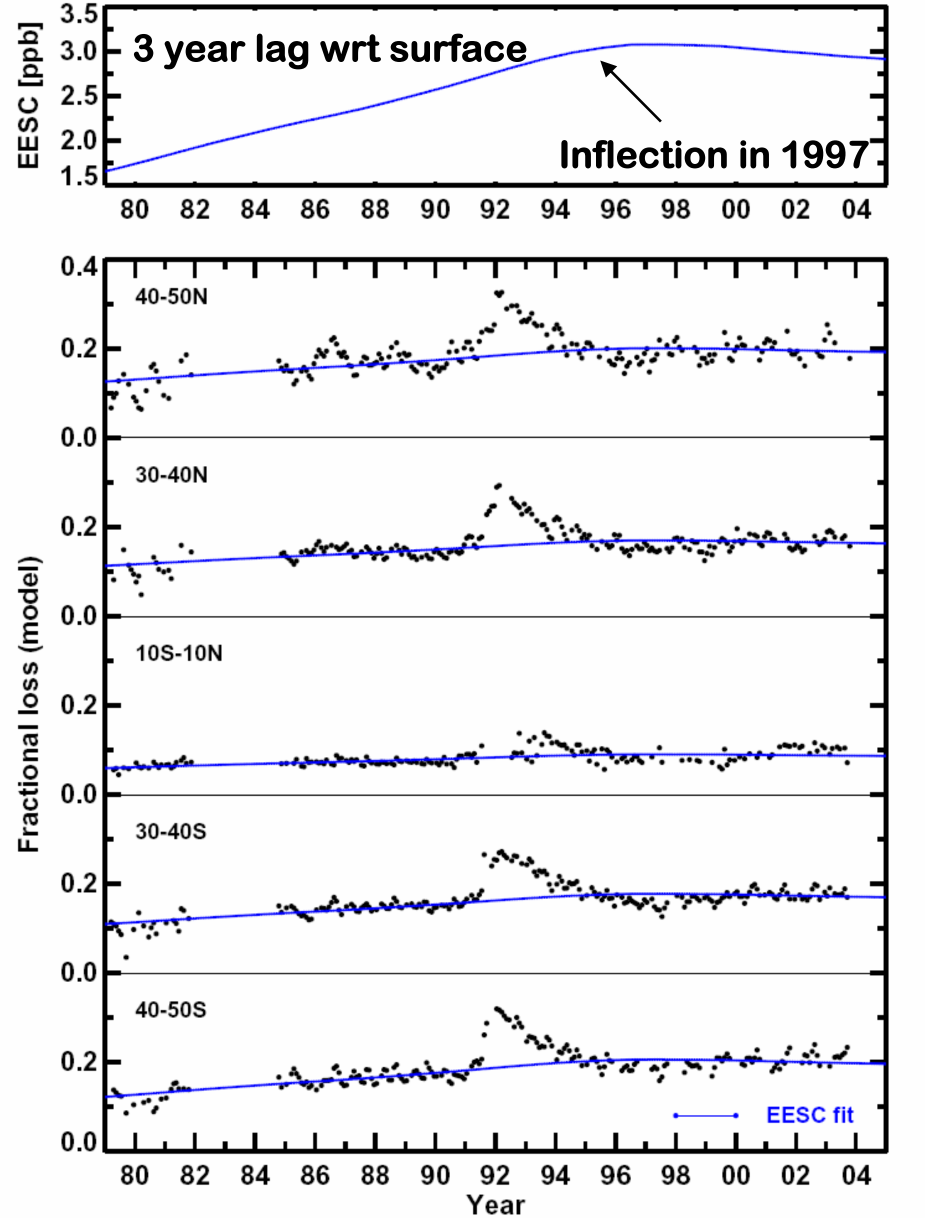
Model constrained in this manner provides accurate description of measured ClO, NO, $NO_2$, OH, and $HO_2$

EESC fit to fractional halogen loss :

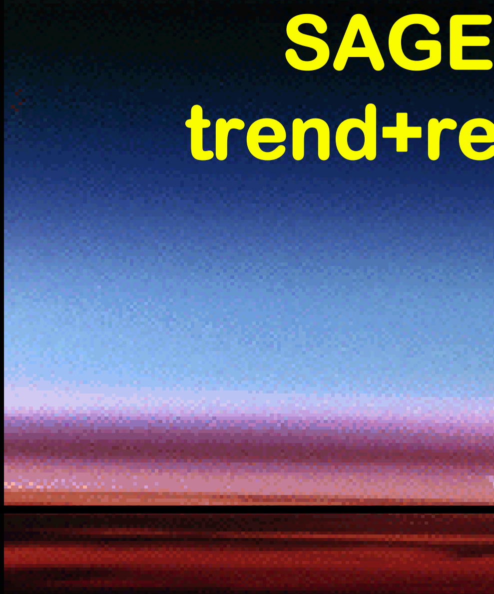
- 5 latitude bands: 50S to 50N
- Ignores Pinatubo period, which is not considered for trend analysis

EESC fit to fractional halogen loss is a refinement that allows attribution analysis to consider effects of changing:

- $H_2O$
- surface area
- dynamically induced changes in $Cl_y$, etc.



# SAGE/HALOE and Halogen loss trend+residual and Cumulative Sums



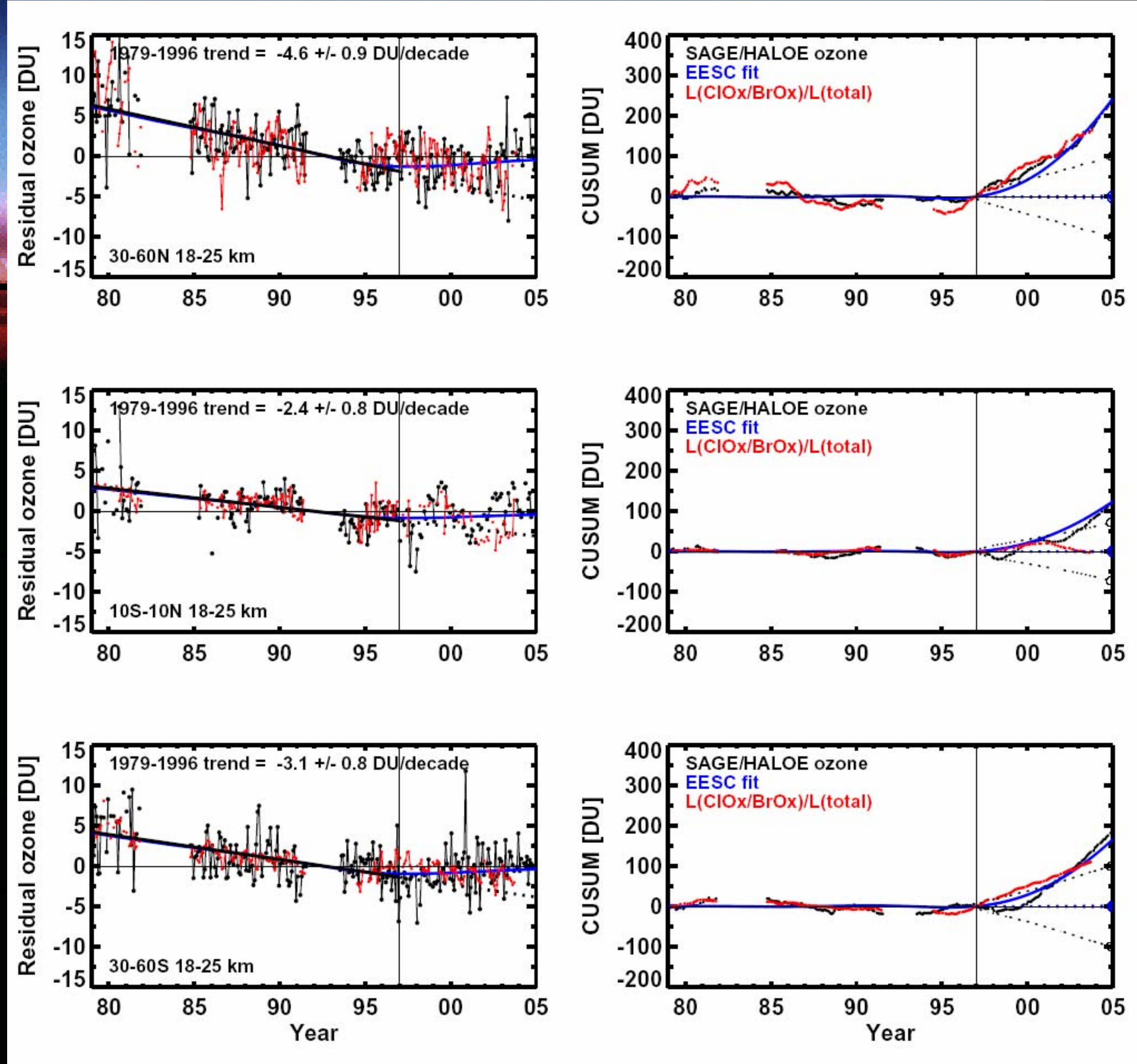
3 latitude bands

<u>18-25 km</u>

SAGE before 1992
HALOE after 1993

CUSUM [DU] - measure of
departure from assumed
linear trend, 1979 to 1997

Change in slope of
residual ozone in 1997 is
matched well by both:
EESC
fractional halogen loss



# SAGE, ozonesonde, EESC fit

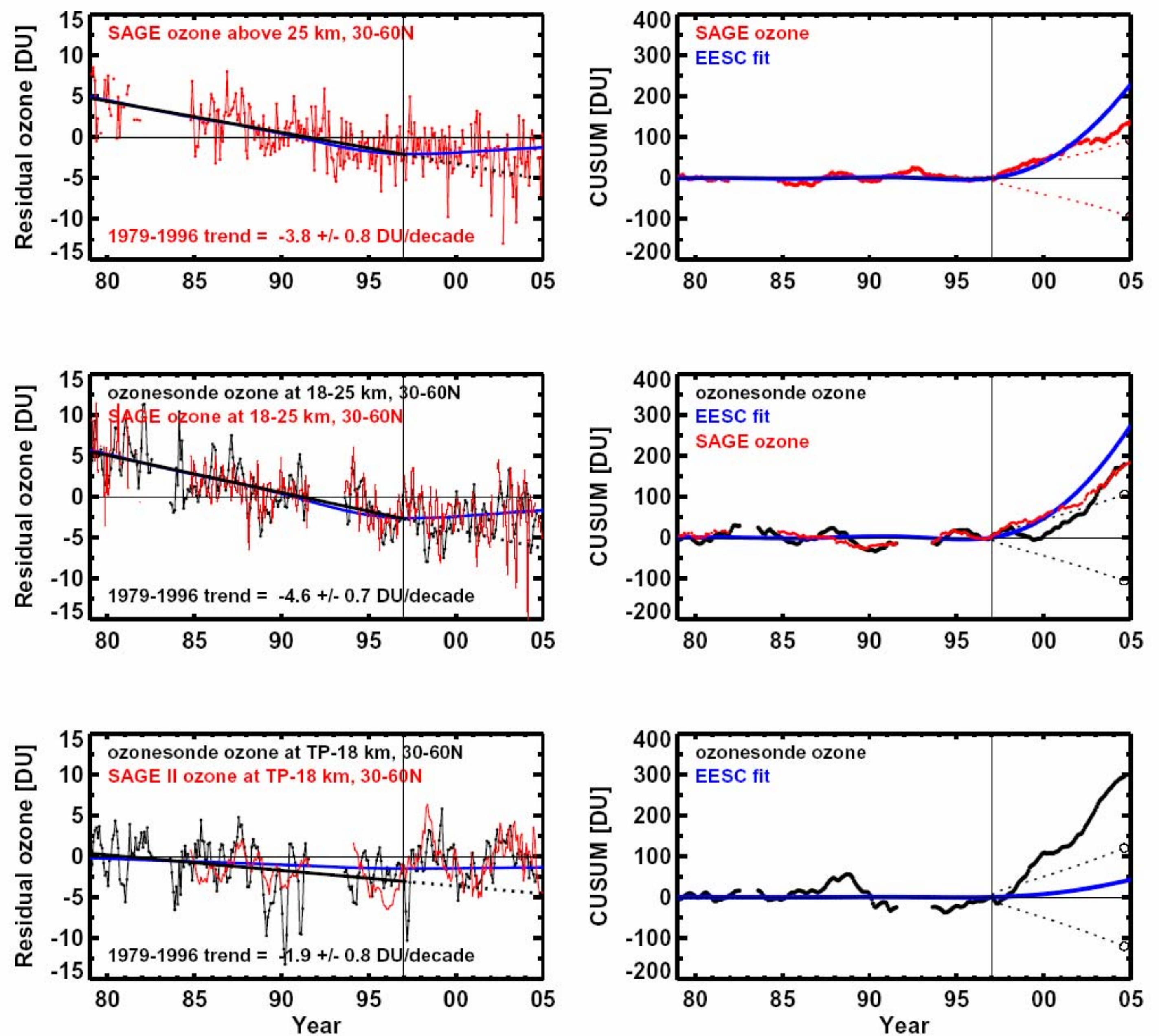
**<u>30N-60N</u>**

**<u>3 Altitude regions:</u>**

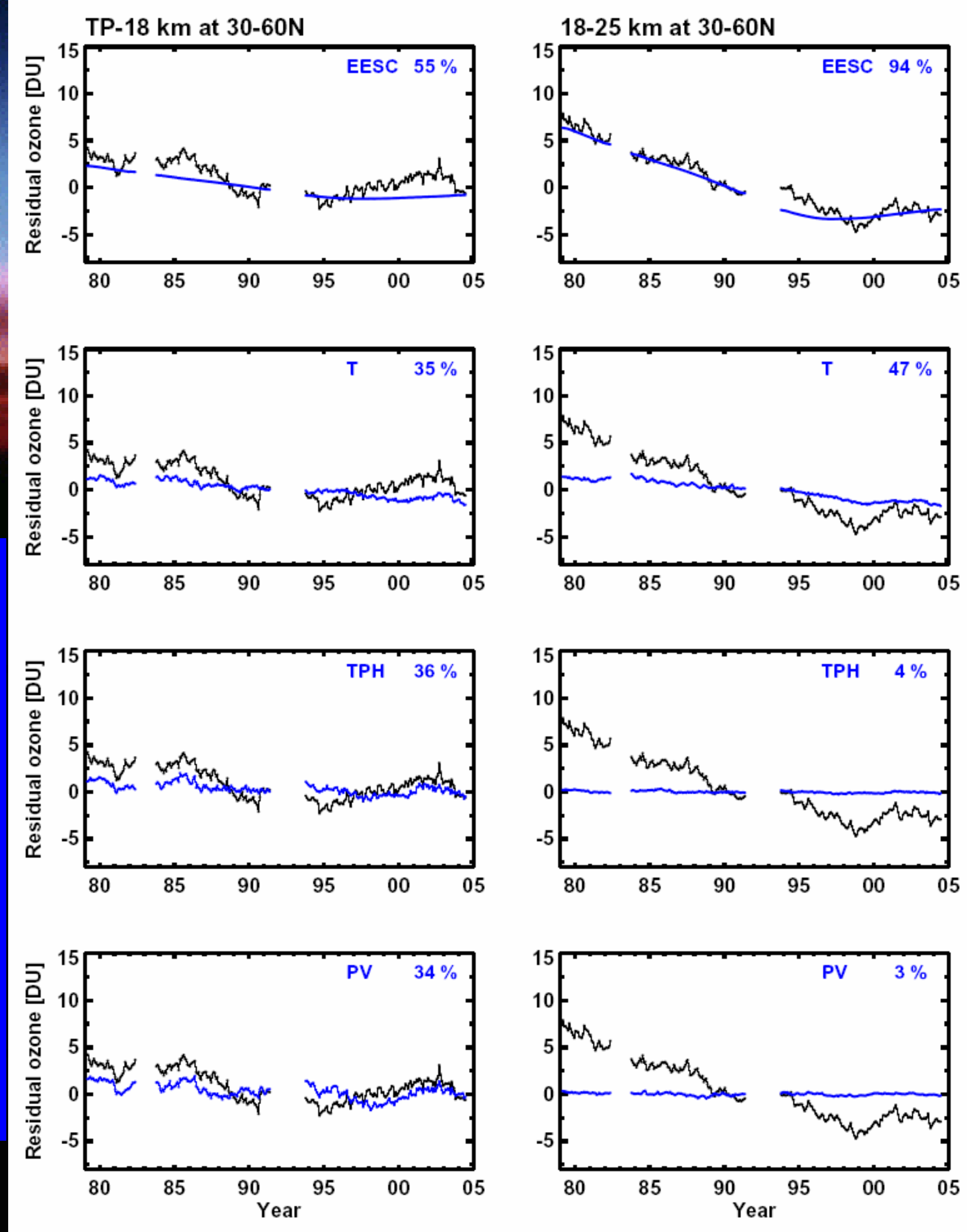
**Z > 25 km**
**18 to 25 km**
**Z < 18 km**

**EESC fit describes $O_3$ changes for:**
**Z > 25 km &**
**18 to 25 km**

**but not for:**
**Z < 18 km**



# Attribution to Dym and Chem: 2 layers




Ozonesonde data, 30N-60N

Chemical proxy = EESC

Dynamical proxies =
Temperature,
Tropopause Height,
PV

18 - 25 km : changes described by EESC

Z < 18 km: changes described
mainly by dynamical proxies

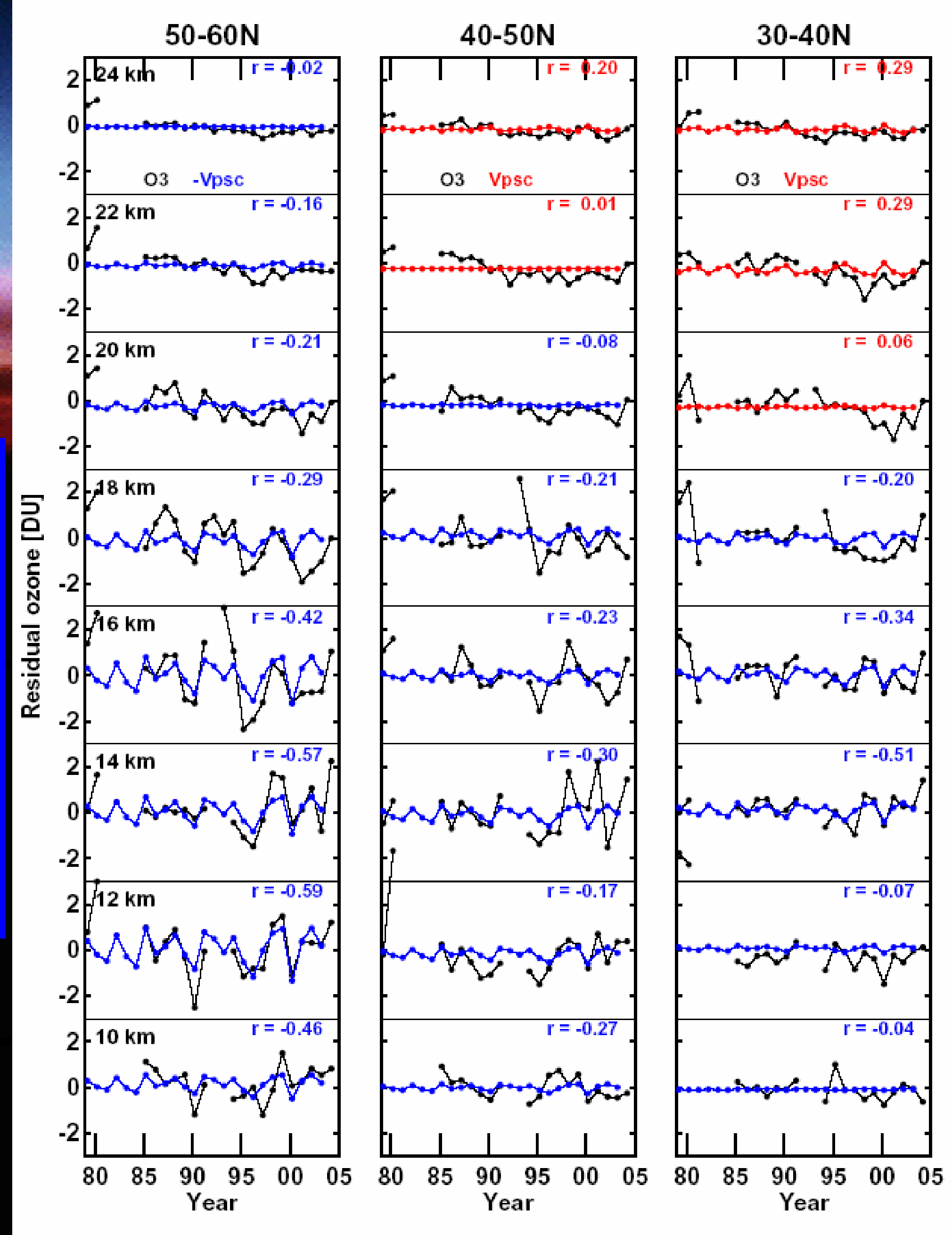
# Polar processing effect on mid latitudes

**SAGE ozone residuals**

**Polar proxy = V psc (inverted on plot)**

**R = regression coefficient between SAGE ozone and Vpsc between February-April**

**Effects of polar processing significant only below 18 km at 50-60N.**



# Vertical partitioning of trends and recovery

| Altitude range | Instrument | trend 1979-1996 [DU/decade] | trend uncertainty 2 sigma | % of total 1979-1996 | CUSUM 1997-2004 [DU] | Average Accumulation rate [DU/decade] | accumulation rate uncertainty 2 sigma | % of total 1997-2005 |
|---|---|---|---|---|---|---|---|---|
| 25 km-TOA | SAGE | -3.8 | 0.8 | 38 | 138 (93) | 3.9 | 2.4 | 22 |
| 18-25 km | ozonesonde | -4.6 | 0.7 | | 180 (106) | 5.1 | 3 | |
| | SAGE | -4.3 | 0.8 | 43 | 184 (104) | 5.1 | 2.7 | 29 |
| | SAGE/HALOE | -4.6 | 0.9 | | 239 (100) | 7.2 | 2.6 | |
| | Average | -4.5 | 1.4 | | | 5.8 | | |
| TP-18 km | ozonesonde | -1.9 | 0.8 | 19 | 296 (120) | 8.4 | 3.4 | 48 |
| Σ layers | SAGE/SAGE/sonde | -10 | 1.4 | | | 17.4 | 5 | |
| Total column | D/B/F | -8 | 1.1 | | 658 (205) | 18.7 | 5.8 | |
| | MOD** | -10.9 | 1.3 | | - | - | | |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# Vertical partitioning of trends and recovery

| Altitude range | | % of total 1979-1996 | | % of total 1997-2005 |
|---|---|---|---|---|
| 25 km-TOA | | 38 | | 22 |
| 18-25 km | | 43 | | 29 |
| TP-18 km | | 19 | | 48 |
| Σ layers | | | | |
| Total column | | | | |


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# Conclusions

Thickness of Earth's stratospheric ozone layer stopped declining after about 1997.

Signature of the observed changes above 18 km altitude is consistent with the timing of peak stratospheric halogen abundances.

Confirms the positive effect of the Montreal Protocol and its amendments.

Observed, large changes in stratospheric ozone below 18 km driven principally by changes in atmospheric dynamics.

Changes are due to natural variability or due to changes in atmospheric structure related to anthropogenic climate change?

Recent record during unusually low levels of stratospheric aerosol loading. Should a major eruption occur, will almost certainly lead to short periods of lower ozone.

Data continuity across AURA period is critical to accurately diagnose changes and attribution of changes in stratospheric ozone.

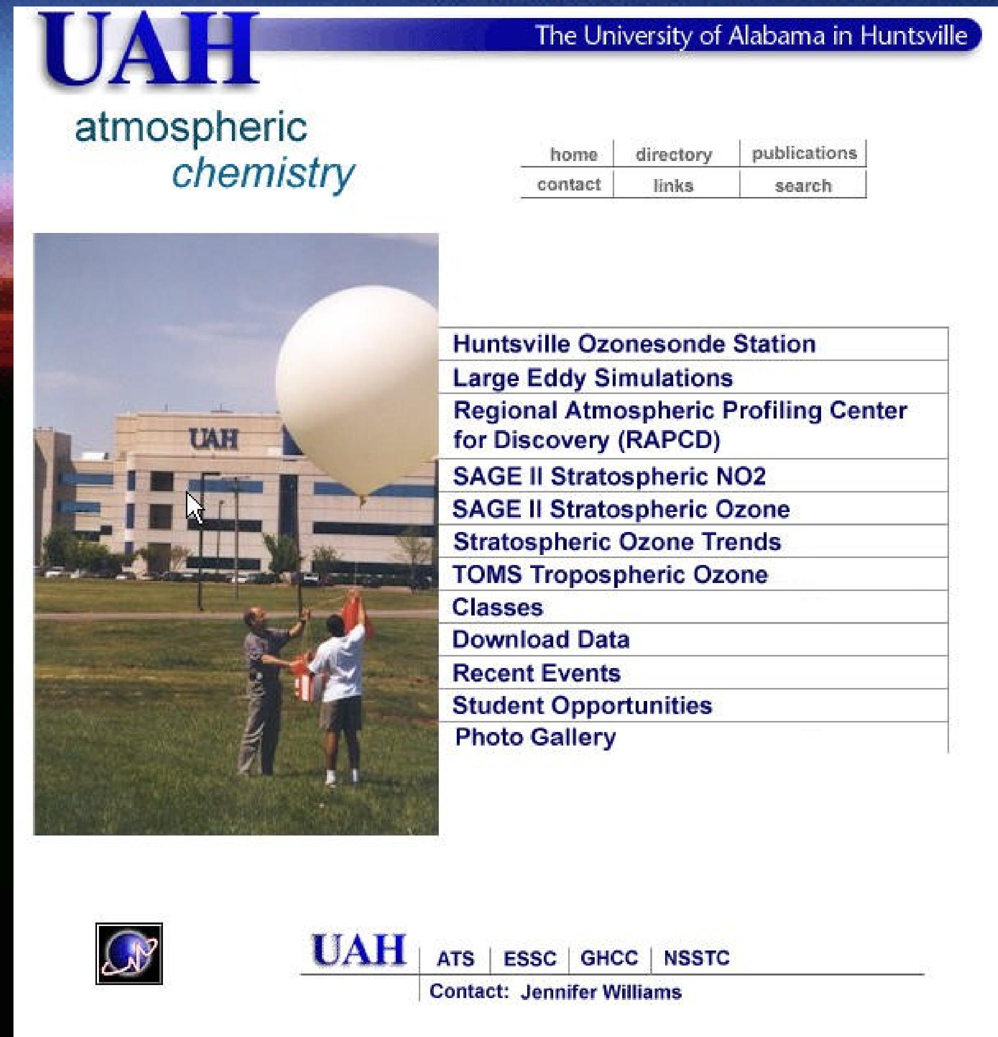
# Dedicated to Greg Reinsel
# 1948 - 2004

Soft spoken gentleman.
Conservative, rigorous scientist.
Consummate statistician.

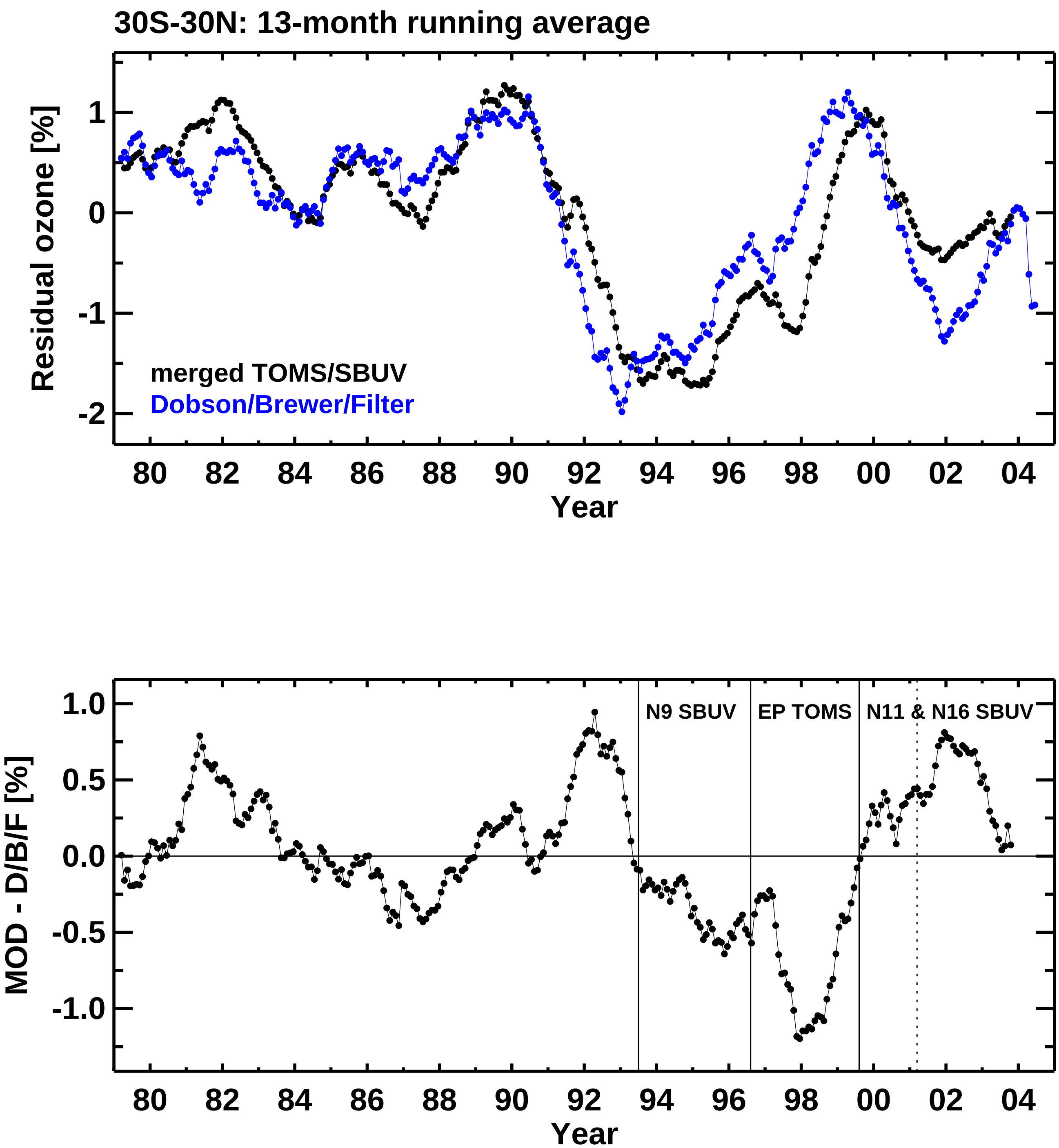
Brought his considerable statistical expertise to the ozone community for 3 decades, primarily in analysis of Dobson and Umkehr ozone trends.

Originated the idea of applying CUSUM technique to ozone measurements for early detection of changes in secular trends: The critical idea for the success of the work presented today.

# http://nsstc.uah.edu/atmchem/




**Support from NASA Earth Science Enterprise**



30S-30N: 13-month running average
Residual ozone [%]
merged TOMS/SBUV
Dobson/Brewer/Filter
1
0
-1
-2
80
82
84
86
88
90
92
94
96
98
00
02
04
Year
MOD - D/B/F [%]
1.0
0.5
0.0
-0.5
-1.0
N9 SBUV
EP TOMS
N11 & N16 SBUV


Figure 2B

# SAGE/HALOE 40km trends and CUSUMs

SAGE observations

Measurements above projected trend

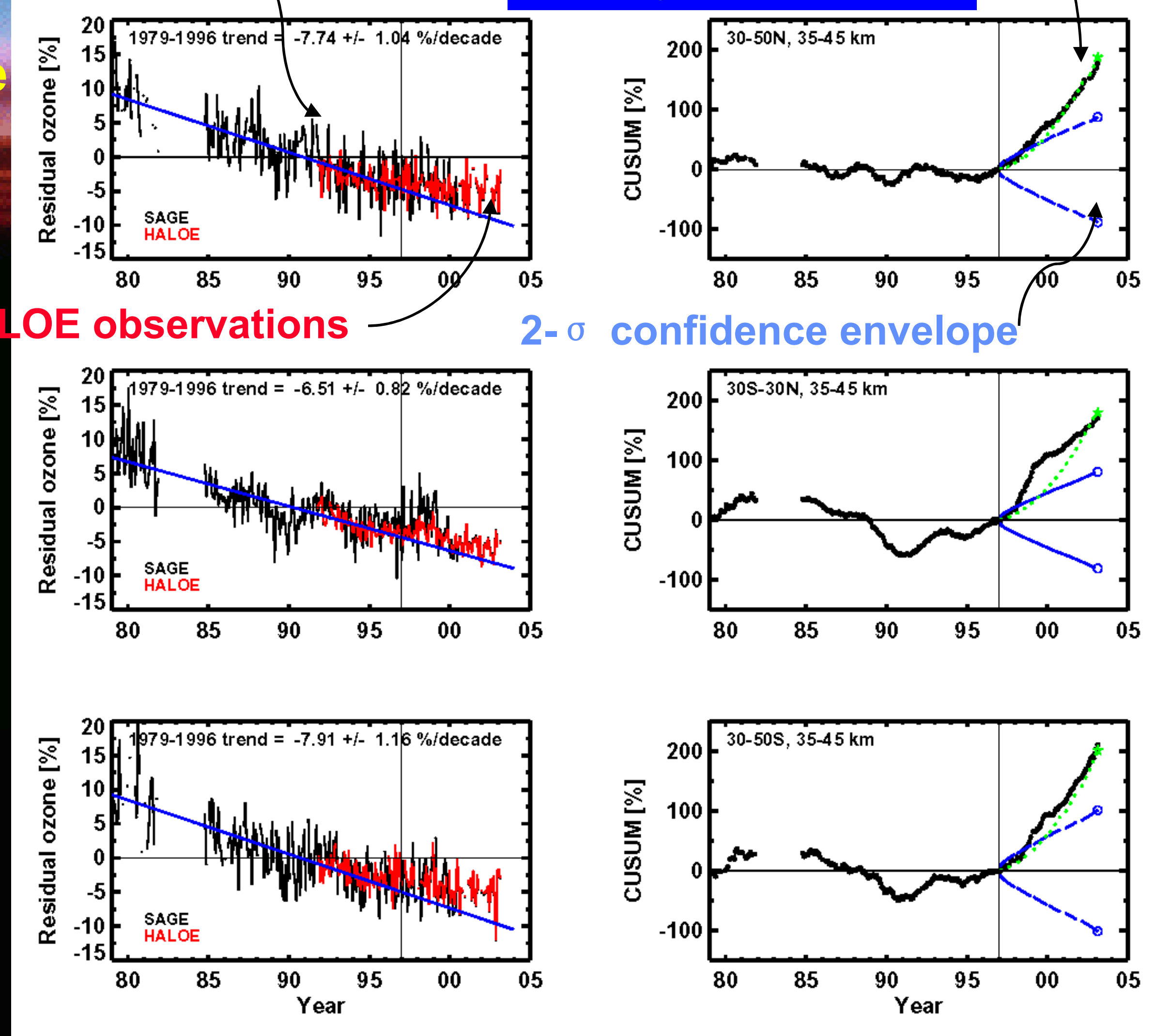
Northern Midlatitude Upper Stratosphere

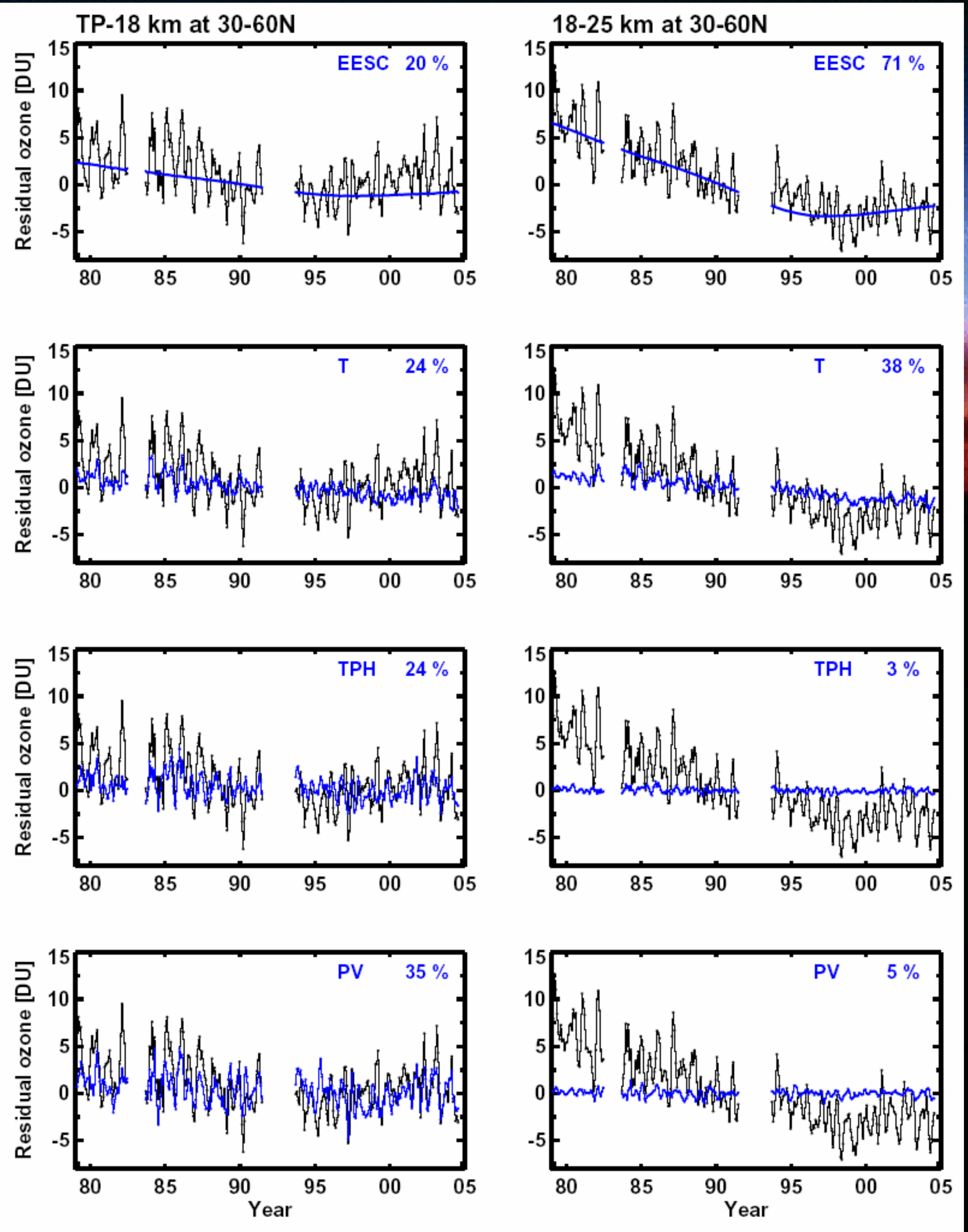
HALOE observations

2-σ confidence envelope

Tropics Upper Stratosphere

Southern Midlatitude Upper Stratosphere





TP-18 km at 30-60N
18-25 km at 30-60N
EESC 20 %
EESC 71 %
T 24 %
T 38 %
TPH 24 %
TPH 3 %
PV 35 %
PV 5 %
Residual ozone [DU]
Year